United States Department of Agriculture
Agricultural Research Service
Pacific West Area
Southwest Watershed Research Center
2000 E. Allen Rd.
Tucson, AZ 85719
Phone: (520) 670-6380
Fax: (520) 670-5550

November 8, 2002

TO: Steven G. Ungar and Valerie Corey

FROM: M. Susan Moran, Ross Bryant, Chandra Holifield, Stephen McElroy, Alfredo Huete, Tomoaki Miura and David Goodrich

SUBJECT: EO-1 Validation Team Progress Report, Year 2002

EO-1 and Landsat Inter-Satellite Comparison at Two Established Arizona Field Sites

Table of Contents

INTRODUCTION

The NASA Landsat program has been dedicated to sustaining data continuity over the twenty-year period during which Landsat Thematic Mapper (TM) and Enhanced TM Plus (ETM+) sensors have been acquiring images of the Earth's surface. In year 2000, NASA launched the Earth Observing (EO-1) Advanced Land Imager (ALI) to test new technology that could improve the TM/ETM+ sensor series, yet ensure Landsat data continuity. Our work quantified the continuity of satellite-retrieved surface reflectance (ρ) for the three most recent Landsat sensors (Landsat 4 TM, Landsat 5 TM and Landsat 7 ETM+) and the EO-1 ALI sensor. In addition, we analyzed the ALI band 4 and 4p for water vapor effects and ALI band 5p for additional information on agricultural crops. Finally, the refined empirical line correction was demonstrated for atmospheric correction of the ALI data.

FIELD WORK

We were fortunate to have many opportunities to acquire coincident Landsat 7 ETM+ and EO-1 Advanced Land Imager (ALI) images at our two study sites, Maricopa Agricultural Center near Phoenix and the Walnut Gulch Experimental Watershed in Southeastern Arizona. Weather and equipment constraints reduced the number of days for our analysis to four at the Maricopa site and one at the Walnut Gulch site. Because we were using a powered parachute platform ground data acquisition, we were able to acquire 15 different ground readings for these days for our analysis (Table 1).

Table 1. Dates and locations for image analysis of Landsat 7 ETM+ and EO-1 ALI sensors.

Date	DOY	Location	# of ground data readings
4/22/2001	112	Maricopa	4
5/24/2001	144	Maricopa	4
5/26/2001	146	Walnut Gulch	5
7/27/2001	208	Maricopa	4
8/29/2001	240	Maricopa	2
9/29/2001	272	Maricopa	2
			Total = 21

Extensive field surveys of MAC were performed for the days that ground data was acquired. Crop cover, crop type, moisture conditions, crop conditions, and fallow field conditions were documented for all working fields on the farm. All this information was integrated into a GIS so that maps of information of interest could be generated. This information was very useful for analyzing anomalous image and field data (e.g. Figure 1).

METHODS AND RESULTS

The following section first presents the results of Landsat sensor pair comparison starting with Landsat 4 TM and Landsat 5 TM, followed by Landsat 5 TM and Landsat 7 ETM+. Next, spectral response and quantization differences between ETM+ and ALI bands are discussed. An equivalent band comparison of these two sensors follows. Then, all the platforms are compared for data continuity. The EO-1 ALI sensor has two bands that fall within the range of Landsat7 ETM+ band 4 which are analyzed. Also, ALI has an additional SWIR band that is evaluated for agricultural applications. In addition to sensor comparisons, the results of applying the REL approach to ALI data are discussed.

The root mean square error (RMSE) statistic is used for all sensor comparisons:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - y_i\right)^2}{n}} \quad , \qquad (1)$$

Where x = ρ measured by the ground-based sensor, y = ρ retrieved from the satellite sensor, and n = number of observations.

Analysis of Landsat 4 TM and Landsat 5 TM imagery

As discussed in our EO-1 progress report in year 2000, because of the paucity of atmospheric field data available for Landsat 4 TM images, we chose to use a trend approach for comparison of the two platforms. For the growing season of 1989, we had four Landsat 4 TM images and five Landsat 5 TM images of the Maricopa Agricultural Center (Table 2). Fortunately, the Landsat 4 TM scenes occurred temporally between the Landsat 5 TM scenes making the data set ideal for analyzing a seasonal trend across the two platforms. Comparing the trend in the field data across time with the trend in the *dn* of the image data from the two platforms allowed us to look for breaks in the trend between the two platforms (Figure 2). Converting the *dn* to radiance was not necessary since, the Landsat 4 TM and Landsat 5 TM headers indicated the same gains and offsets. Visual inspection of data in Figure 2 indicated that only band 1 of Landsat 4 TM does not follow the expected seasonal trend defined by the ground data.

Table 2. Dates for image analysis of Landsat 4 and Landsat 5 sensors.

Date	DOY	Sensor
5/31/1989	151	Landsat 5 TM
6/16/1989	167	Landsat 5 TM
6/25/1989	175	Landsat 4 TM
7/2/1989	183	Landsat 5 TM
7/25/1989	207	Landsat 4 TM
8/19/1989	231	Landsat 5 TM
8/27/1989	239	Landsat 4 TM
9/4/1989	247	Landsat 5 TM
9/12/1998	255	Landsat 4 TM

To quantify differences in trends between ground data and the Landsat 4 TM – Landsat 5 TM dataset, we normalized the dataset and took the difference of temporally adjacent values of the normalized *dn* value and compared them to associated difference values of the normalized reflectance data. Except for the first two days, the satellite data alternated temporally between the two Landsat TM sensors. By eliminating the first day, each difference value for the satellite dataset represents Landsat 4 TM and Landsat 5 TM. Values of the difference between slopes of temporally adjacent ground data and slopes of satellite data are significantly higher for band 1 compared to the other bands (Figure 3).

The second approach for the analysis utilized the Refined Empirical Line (REL) method described in the progress report for 2000 (Moran, et. al., 2001). Reflectances derived from Landsat *dn* with the REL method were compared to ground reflectances across both sensors (Figure 4). Root mean square error (RMSE) for the Landsat 4 TM sensor and the Landsat 5 TM sensor were very similar (Table 3). RMSE for band one for Landsat 4 was also similar indicating that with, the correct calibration coefficient, data continuity across these sensors is very good.

Table 3. Root mean square error (RMSE) for ground reflectance and reflectance derived using the Refined Empirical Line method for Landsat 4 TM and Landsat 5 TM sensors.

	Band 1	Band 2	Band 3	Band 4
Landsat 4 TM	0.008	0.006	0.009	0.011
Landsat 5 TM	0.015	0.006	0.009	0.023

Atmospheric characterization for Landsat 5 TM and Landsat 7 ETM+ comparison

Comparison of the Landsat 5 TM and Landsat 7 ETM+ sensors involved extensive use of a computer program developed at the University of Arizona that models the atmosphere. The only inputs that require the collection of data with a specialized instrument are optical depths. Optical depth was obtained with a solar radiometer. We used a Reagan radiometer built by the University of Arizona, which can measure optical depths at 10 different wavelengths. The radiometer actually measures energy intensity from the sun as a function of air mass. Post-processing of the data resulted in optical depth divided into the following components: molecular optical depth, aerosol optical depth and ozone optical depth. One other parameter necessary for the atmospheric modeling code, the Junge parameter, was also derived from the solar radiometer data.

When all the necessary input parameters were derived for a particular overpass, the atmospheric modeling program was run resulting in a matrix of numbers that defined the relationship between ground reflectance and at-sensor radiance. This relationship was used to derive a predicted reflectance at a location in the satellite image where ground reflectance had been acquired. Comparing these two reflectances across platforms allowed for an independent test of sensor continuity after accounting for atmospheric effects.

Analysis of Landsat 5 TM and Landsat 7 ETM+ imagery

Twelve Landsat 5 TM and thirteen Landsat 7 ETM+ images were analyzed in this study. More than one target was analyzed for several images for a total of 38 targets, nineteen for each platform. Landsat 5 TM images were acquired from 1985 to 1992 and Landsat 7 ETM + images were acquired from 1999 to 2001 (Table 4).

Table 4. List of images used for the Landsat 5 TM – Landsat 7 ETM+ analysis.

Date	DOY	Sensor	Location
3/20/1985	79	Landsat 5 TM	Maricopa
7/23/1985	204	Landsat 5 TM	Maricopa
8/9/1985	220	Landsat 5 TM	Maricopa
10/27/1985	300	Landsat 5 TM	Maricopa
4/21/1986	111	Landsat 5 TM	Maricopa
6/24/1986	175	Landsat 5 TM	Maricopa
5/31/1989	151	Landsat 5 TM	Maricopa
4/23/1992	114	Landsat 5 TM	Walnut Gulch
6/10/1992	162	Landsat 5 TM	Walnut Gulch
7/12/1992	194	Landsat 5 TM	Walnut Gulch
9/30/1992	274	Landsat 5 TM	Walnut Gulch
11/1/1992	306	Landsat 5 TM	Walnut Gulch
11/17/1992	322	Landsat 5 TM	Walnut Gulch
9/24/1999	267	Landsat 7 ETM+	Maricopa
9/26/1999	269	Landsat 7 ETM+	Walnut Gulch
7/26/2000	208	Landsat 7 ETM+	Walnut Gulch
9/12/2000	256	Landsat 7 ETM+	Walnut Gulch
9/26/2000	270	Landsat 7 ETM+	Maricopa
9/28/2000	272	Landsat 7 ETM+	Walnut Gulch
4/22/2001	112	Landsat 7 ETM+	Maricopa
5/24/2001	144	Landsat 7 ETM+	Maricopa
5/26/2001	146	Landsat 7 ETM+	Walnut Gulch
7/27/2001	208	Landsat 7 ETM+	Maricopa
8/29/2001	240	Landsat 7 ETM+	Maricopa
9/29/2001	272	Landsat 7 ETM+	Maricopa

The Landsat 5 TM to Landsat 7 ETM+ comparison was conducted with data acquired over a 17-year period from 1985 to 2000. Overall, there was a good relation between satellite-retrieved ρ from the Landsat 5 TM and Landsat 7 ETM+ sensors and the ground-measured ρ (Figure 5). For all bands and all dates, the RMSE between satellite- retrieved and ground-measured ρ was 0.021 for Landsat 5 TM data, and RMSE was 0.025 for Landsat 7 ETM+ data. The RMSE calculated for each band separately (Table 5) showed similar uncertainty, with RMSE for bands 1-4 ranging from 0.016 (Landsat 5 TM band 2) to 0.038 (Landsat 7 ETM+ band 4). RMSE for Landsat 5 TM, bands 5 and 7, were not calculated because ground-measured ρ values for these bands were not available.

Table 5. Root mean squared error (RMSE) between ground measured reflectance and atmospherically corrected satellite-based reflectance from Landsat 5 TM and Landsat 7 ETM+ sensors.

Sensor	Band 1	Band 2	Band 3	Band 4
Landsat 5 TM	0.017	0.016	0.022	0.027
Landsat 7 ETM+	0.022	0.018	0.022	0.038

ASD spectral band comparison for Landsat 7 ETM+ and EO-1 ALI sensors

The EO-1 ALI sensor contains spectral bands that are quite similar to Landsat 7 ETM+ bands except in Landsat 7 ETM+ band 4, where there are two narrower EO-1 ALI bands that occur within the Landsat 7 ETM+ band 4 (Figure 6). Because our ground reflectance measurements for Landsat 7 ETM+ and EO-1 ALI were taken with an Analytical Spectral Device (ASD) full spectrum (FS) hyperspectral radiometer, we were able to consolidate our ground data to both Landsat 7 ETM+ spectral bands and EO-1 ALI spectral bands. We used ground reflectance data from Walnut Gulch and Maricopa from 2 different days to compare reflectance values between similar EO-1 ALI and Landsat 7 ETM+ bands (Figure 7, Table 6). As expected, the reflectances for similar bands between the platforms were extremely close with the highest RMSE of 0.07 in band 4. This is to be expected because the spectral response functions between ETM+ and ALI are the most different in comparison to the other equivalent bands.

Table 6. Root Mean Square Error for ground reflectance calculated for Landsat 7 ETM+ bands and comparable EO-1 ALI bands. Measurements taken with an Analytical Spectral Device FR at Walnut Gulch and Maricopa during 2 different dates. Total of 16 readings.

Landsat 7 ETM+ and EO-1 ALI bands	RMSE
B1	0.0018
B2	0.0041
B3	0.0005
B4	0.0066
B5	0.0002
B7	0.0023

EO-1 ALI and Landsat 7 ETM+ quantization

Because EO-1 ALI level 1R images are 12 bit data, quantization is necessarily improved in comparison to 8 bit Landsat 7 ETM+. But a better quantization is useful only if the radiometric range of the target can not be captured at the standard Landsat 7 ETM+ 8 bit quantization . At least one of the Landsat 7 ETM+ images in this analysis had saturation in bands 5 and bands 7 (Figure 8). The associated EO-1 ALI image exhibited no saturation in these bands indicating that a broader dynamic range is necessary to fully capture the radiometric information in this image. Figure 9 shows the range of digital counts for all bands for both Landsat 7 ETM+ and EO-1 ALI sensors. With the exception of Band 7, the range in EO-1 ALI digital counts is greater by an order of magnitude or more. It should be noted that these values are not directly comparable since the EO-1 ALI Level 1R data is 10 bit data scaled to 16 bit data. Band 7 has a similar range of *dn* for both platforms. Since band 7 reflects much less energy than the other bands, sensor sensitivity could be a limiting factor.

Analysis of Landsat 7 ETM+ and EO-1 ALI imagery

Fortunately, all the ground data for the EO-1 ALI – Landsat 7 ETM+ analysis were acquired using an ASD FS radiometer. This allowed us to analyze the two shortwave infrared bands along with the visible and NIR bands. Recall that twenty one data points from six different days at two sites (Table 1) were used for our analysis of these two platforms. The procedure for this analysis was identical to our analysis of the Landsat 5 TM and Landsat 7 ETM+ sensors; that is, modeled ground reflectance based on sensor data and atmospheric data were compared to ground reflectance (Figure 10). RMSE for all bands was 0.028 for EO-1 ALI and 0.024 for Landsat 7 ETM+. Each band of the sensors was also compared (Figure 11) and the RMSE statistic calculated (Table 7). The RMSE of ETM+ and ALI band 4, 0.057 and 0.037 respectively, were higher than RMSE of all other bands, which ranged from 0.013 to 0.032. This was due to the fact that the average reflectance for band 4 was 0.42, whereas average reflectance in all other bands ranged from 0.08 (band 1) to 0.29 (band 5). All RMSE values for equivalent ETM+ and ALI bands were within 0.032 reflectance, indicating very good agreement between the sensors.

Table 7. Root mean squared error between atmospherically corrected satellite based reflectance and ground reflectance for Landsat 7 ETM+ and ALI.

Sensor	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Landsat 7 ETM+	0.023	0.024	0.027	0.057	0.032	0.013
EO-1 ALI	0.021	0.020	0.023	0.037	0.020	0.020

Table 8. Root mean squared error between atmospherically corrected satellite based reflectance for Landsat 7 ETM+ and atmospherically corrected satellite based reflectance for EO-1 ALI.

Sensor	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
ALI_ETM+	0.003	0.012	0.009	0.018	0.031	0.020

The robust relationship between EO-1 ALI and Landsat 7 ETM+ atmospherically corrected satellite based reflectances indicates that data continuity between the platforms is excellent. Larger error in the relationship between the atmospherically corrected satellite based and ground reflectance for both platforms is a result of error inherent in obtaining reliable optical depths for inputs into the atmospheric model. Since the platforms were acquiring imagery coincidently, the atmospheric inputs were the same so the same error was propagated. The similar atmospherically corrected satellite based reflectances for both platforms indicate the relative radiometric stability of the satellites throughout the time of this project.

<u>Analysis across all platforms</u>

The statistical comparisons between sensor pairs reported in previous subsections were based on different measurement and processing methods. Thus, the RMSE in one sensor-to-sensor comparison would not be comparable with that of another sensor-to-sensor comparison. To evaluate the data continuity of all four sensors over time and minimize the method-induced differences, the absolute difference of the RMSE between sensor pairs was determined (Table 9). Based on that statistic, the highest absolute sensor-to-sensor difference was only 0.020 for band 4 for EO-1 ALI and differences for all other bands and sensors were less than 0.013 reflectance (Table 9). These results were consistent with the comparisons of reflectances (RMSE) retrieved from ALI and ETM+. The basic conclusion of this analysis is that data continuity across all the Landsat sensors and the ALI sensors is excellent.

Table 9. Absolute difference in RMSE of atmospherically corrected satellite-based reflectances and ground-based reflectances between sensor pairs.

Sensor	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
TM 5-TM 4	0.007	0.000	0.000	0.012		
ETM+-TM 5	0.005	0.002	0.000	0.011		
ALI-ETM+	0.002	0.004	0.004	0.020	0.012	0.007

<u>Evaluation of EO-1 ALI band 5p</u>

The ALI sensor offers an additional short wave infrared (SWIR) band called 5p, which ranges from 1.2 to 1.3 *um*. This band was added because it corresponds to a strong atmospheric window in the SWIR spectrum, which might be useful in agriculture and forestry applications (Dr. James Irons, NASA GSFC, personal communication). In this study, it was possible to compare the satellite-retrieved ρ values for three ALI SWIR bands for the 21 ground targets at MAC. The simultaneous field surveys of the MAC site near the times of the overpasses provided descriptive data for this qualitative analysis.

The reflectances of the 21 targets measured in ALI bands 5 and 7 showed a wide range of reflectance and a strong correlation between the reflectance measured in ALI bands 5 and 7 (Figure 14). This was not the case for reflectances retrieved from ALI in band 5p. The vast majority of the retrieved reflectances in ALI band 5p were close to a value of ρ = 0.40. The targets that deviated most from ρ = 0.40 in ALI band 5p were examined for field data information. Target number 15 had the lowest reflectance and deviated furthest from the cluster. This target was a hesperaloe crop, a yucca-like plant used to make high quality paper, that had a canopy with much different structural characteristics than any field crop targets in this analysis. Another low reflectance was target 3, a pecan orchard that had a canopy with a more complex structure than a common field crop. Target 12 had the same reflectance as target 3 and was mature wheat, characterized by dense heads protruding far above the leaf canopy. The highest reflectance was target 16, which was 5-meter wide alternating strips of wheat stubble and soil. Interestingly, the four targets with the furthest deviation from the cluster were the most structurally heterogeneous targets. The other study sites were cotton or alfalfa crops, weeds, soil or semi-arid grasslands.

Evaluation of EO-1 ALI Band 4p

The ALI sensor offers two NIR bands that are narrower than ETM+ band 4, but fall within the spectral range of ETM+ band 4 (Figure 6d). The purpose of the reconfiguration of band 4 in ALI was to avoid the relatively strong water absorption that occurs in the middle of Landsat 7 ETM+ band 4 (0.810 – 0.840 um). In our study, we found that columnar water vapor ranged from 1-3 cm and water vapor absorption reduced satellite-retrieved ρ in ETM+ band 4 up to 10%. Ground-based measurements of ρ were compared to satellite-retrieved ρ, with and without water vapor correction for these 3 bands (Table 10). For ETM+ band 4, accounting for water vapor improved the relationship with ground data; the RMSE was reduced from 0.078 to 0.057. The RMSE for ALI band 4 decreased slightly from 0.053 to 0.041. The RMSE for ALI band 4p was the smallest of all, and there was a negligible difference between the two cases. These results showed that, for our data set, ALI band 4p was essentially unaffected by atmospheric water absorption.

Table 10. Root mean squared error (RMSE) reflectance retrieved from Landsat 7 ETM+ band, EO-1 ALI band 4 and 4p and associated ground reflectance. Two cases are presented: atmospheric correction without water vapor correction and with water vapor correction.

Band	Without water vapor correction	With water vapor correction
ETM+ Band 4	0.078	0.057
ALI Band 4	0.052	0.041
ALI Band 4p	0.037	0.034

In terms of data continuity between ETM+ and ALI, it was demonstrated that ALI band 4 and ETM+ band 4 had very similar reflectance characteristics, at least for a semi-arid grassland (Figure 7). However, when comparing at-satellite radiances between these two bands, caution should be exercised due to the different atmospheric water absorption.

Refined empirical line correction applied to ALI data

The 21 data points used for validation of the ALI sensor were also used to analyze the Refined Empirical Line (Moran et al., 2001) method of converting image *dn* to reflectance. The REL approach uses two reflectance-*dn* data pairs to develop a relationship between the *dn* of an uncalibrated image and ground reflectance. One data pair describes the *dn* at $\rho = 0$ which is retrieved from a radiative transfer code. The other data pair is the *dn* of a relatively bright target of known reflectance in the image to be converted to reflectance.

On each date, the target with the highest ground-measured ρ in each band was chosen as "the bright target" for that image, and it was used with the *dn* at 0 reflectance in Table 11 to compute the REL *dn*-to-ρ relation

$$\rho_{REL} = a + b(dn), \quad (2)$$

where $\rho_{\lambda REL}$ is ρ retrieved from ALI using the REL approach, and *a* and *b* are the offset (i.e., *dn* at ρ=0) and slope of the linear relation, respectively. All other targets were used for REL validation.

Table 11. ALI dn for targets of zero surface reflectance (ρ) as computed from the radiative transfer model (RTM) for 6 dates at MAC and WGEW.

ALI Spectral Band	Average *dn*	Standard Deviation
1p	1399.2	71.6
1	864.7	44.3
2	371.5	21.1
3	183.3	13.6
4	70.0	8.1
4p	40.9	5.9
5p	3.9	1.6
5	2.2	1.3
7	0.3	0.2

For comparison with $\rho_{\lambda REL}$, ρ was also retrieved from ALI *dn* using two other approaches. In one case, ρ was retrieved using only the ρ of the bright target, where

$$\rho_{BT}=b(dn), \tag{3}$$

and ρ_{BT} represents ρ_λ retrieved from ALI using the bright target only. In the other, ALI *dn* was converted to spectral radiance (*L*) using the sensor calibration coefficients, and ρ was computed without atmospheric correction, where

$$\rho_{\lambda NC} = (\pi L_\lambda d^2) / (I_\lambda \cos(\theta)) \tag{4}$$

and ρ_{NC} represents ρ retrieved from ALI with no atmospheric correction, *d*=earth to sun distance, *I*= mean solar exoatmospheric spectral irradiance, and *θ*=solar zenith angle.

Reflectances derived using all approaches (Eqs. 2-4) were validated by comparison with ground-measured ρ_λ for the 15 validation targets. The mean absolute percent difference ($\Delta_{\%}$) of ρ_{REL} and ground-measured ρ was computed as

$$\Delta_{\% REL} = \left(\sum_{i=1}^{n} \left(\left| \rho_{\lambda RELi} - \rho_{\lambda i} \right| / \rho_{\lambda i} \cdot 100 \right) \right) / n \tag{5}$$

where n is the number of targets (15) used in the analysis. The $\Delta_{\%}$ computed for validation of ρ_{REL}, ρ_{BT}, and ρ_{NC} are distinguished by subscripts as $\Delta_{\%REL}$, $\Delta_{\%BT}$, and $\Delta_{\%NC}$, respectively.

The ALI values of *dn* at ρ=0 are reported here (Table 11). These values are highest for the visible bands, ranging from 1399.2 in band 1p (blue spectrum) to 183.3 in band 3 (red spectrum). The values were moderately small for the NIR bands (~50 *dn*) and negligible for the SWIR bands <4 *dn*). This is because atmospheric scattering is greatest in the shorter wavelengths, and the offset in the REL equation reflects the signal contributed by atmospheric scattering.

The ρ retrieved from ALI using the REL (ρ_{REL}) compared well with the ground-measured ρ for the 15 targets measured during the six ALI overpasses at MAC and WGEW (Figure 15, Table 12). Values of $\Delta_{\%REL}$ ranged from 16 to 65% in the visible spectrum, 6 to 7% in NIR, and 6 to 22% in SWIR. The relatively higher $\Delta_{\%REL}$ in the visible bands is largely due to the lower ρ in these bands over vegetated targets, resulting in larger $\Delta_{\%REL}$ even though the absolute differences between ρ and ρ_{REL} were less than 0.02.

Table 12. The mean absolute percent difference ($\Delta_{\%}$) between ground-measured ρ_{λ} and ρ retrieved from ALI using REL ($\Delta_{\%REL}$), ρ retrieved from ALI using only the bright target ($\Delta_{\%BT}$), and ρ retrieved from ALI with no atmospheric correction ($\Delta_{\%NC}$)

ALI Spectral Band	Δ%REL	Δ%BT	Δ%NC
1p	16.7	143.8	290.9
1	65.2	125.2	198.3
2	33.5	52.1	55.6
3	53.1	74.0	73.8
4	6.2	6.3	8.8
4p	7.1	7.1	9.7
5p	6.6	6.7	7.2
5	11.0	11.2	8.5
7	22.0	22.2	14.4

When only the bright target was used for reflectance retrieval (Eq. 3), the ρ_{BT} compared well with ground-measured ρ for the NIR and SWIR bands, and $\Delta_{\%BT}$ was similar to $\Delta_{\%REL}$ (Table 12). For the visible bands, $\Delta_{\%BT}$ was significantly higher than $\Delta_{\%REL}$. This decrease in accuracy was due to fact that Eq. (3) does not correct well for atmosphere scattering, which is quite large in the visible bands. On the other hand, reflectance retrieval with one ground target (Eq. 3) worked as well as with two targets (Eq. 2) in the NIR and SWIR bands. In these longer wavelengths, the signal is primarily attenuated by atmospheric water vapor.

When ρ was retrieved from ALI with no atmospheric correction (Eq. 4), there were large errors in the visible bands ($\Delta_{\%NC}$ was nearly 300% in band 1p) and minimal error in the NIR and SWIR bands (Figure 16, Table 12). In southern Arizona on cloudfree days, the water vapor attenuation is minimal, and these results showed that there was very little atmospheric correction needed. In fact, for ALI band 7, the error in uncorrected reflectance ($\Delta_{\%NC}$ = 14%) was less than that for the REL-corrected reflectances ($\Delta_{\%REL}$ = 22%). This points out an important aspect of the REL approach: The accuracy of empirical line corrections (both EL and REL) depends almost exclusively on the accuracy of the characterization of the calibration targets. In our case, the corrections in the SWIR bands were very slight, and a minor inaccuracy in the measurement of ρ for the WGEW bright target resulted in a slight overcorrection of the image.

OTHER PROJECTS SUPPORTED BY THIS GRANT

EO-1 ALI and Landsat ETM+ comparison in Argentina

Chandra Holifield and Stephen McElroy from the USDA-ARS Southwest Watershed Research Center in Tucson, AZ participated in a 16-day international fieldwork campaign in Argentina in January 2002. This research was undertaken in coordination with Dr. José Paruelo from the Universidad de Buenos Aires. The USDA-ARS Office of International Research Programs provided travel funding for the project.

The purpose of the fieldwork was to gather ASD and IRT data from a series of grassland sites near Esquel and to assist Dr. Paruelo with ASD measurements of plots at Rio Mayo. The research objectives were to assess the data continuity of a new satellite sensor (EO-1 ALI) with the conventional Landsat 7 ETM+ sensor for naturally vegetated sites and to begin investigation of remote sensing applications at "twin" grassland sites in the U.S. and Argentina. The overall goal of this research is to provide high-tech tools for rangeland managers that can assist in decision-making for increased profitability and ecological sustainability.

During the field campaign, due to equipment limitations, the atmosphere was not characterized so an atmospherically corrected at sensor reflectance was not computed. Instead, reflectance ground data at a nearby airport was acquired to characterized for a pseudo-invariant object (the airport tarmac). Current work includes using this ground data to apply the REL method to both the ETM+ and ALI images.

Temporal analysis of WDI using three Landsat sensors

Results from the EO-1 and Landsat inter-satellite comparison project made possible a study, which used a ten-year series of Landsat imagery to detect temporal and spatial changes in grassland transpiration. Imagery from sensors aboard three consecutive Landsat satellites, Landsat 4 TM, Landsat 5 TM, and Landsat 7 ETM+ was used for this study. Commonly, temporal studies are limited to the lifespan of a single satellite sensor to avoid the uncertainty associated with data from different sources. However, because of the data continuity project, this uncertainty, to a large degree, was eliminated.

In this study, the water deficit index (WDI), which estimates relative evapotranspiration rates based on meteorological data and the relation between surface reflectance and temperature, was derived from the Landsat data series of the WGEW during the summer monsoon period (Holifield et al., 2002).

Through this study, it was demonstrated that surface reflectance and temperature measurements from the three sensors could be combined without sacrificing product accuracy. Results showed that WDI was a measure of transpiration when evaporation was negligible and WDI was useful for mapping temporal and spatial grassland variability, as well as topographically-induced vegetation differences. This combination of Landsat-4, -5, and -7 is a powerful source of information for temporal studies of natural resources.

CONTINUING WORK

We recently received a one-year, no-cost extension on this grant for continuing EO-1 related research. We expect to focus on three areas during this time. 1. Applying remotely sensed data to a rangeland growth model, 2. Analysis of differences in the panchromatic band between ETM+ and ALI, and 3. The evaluation of water sensitive bands that can be retrieved from the Hyperion sensor.

Synthesis of rangeland plant growth model with remotely sensed data

In June 2002, a post-doctoral scientist was hired to integrate remotely sensed data into a physically based model designed to simulate the complexity of rangeland ecosystems. The SPUR model (Simulation of Production and Utilization of Rangelands) was developed by ARS to specifically address the rangeland environment.

The post-doctoral scientist is tasked with adapting the model to accept inputs from remotely sensed data for the purpose of model calibration and validation. Conversely, inputs required by the model can be determined from remotely sensed imagery. Soil water evaporation, and LAI are examples of inputs that can be derived from remotely sensed data.

Walnut Gulch will be the validation site for this project. It is extremely well instrumented and ARS Tucson has Landsat images dating back 10 years as well as recent ALI and Hyperion images. ALI and Hyperion images from the extended mission will also be used.

Evaluation of ALI panchromatic band

At present, we are in the process of comparing the EO-1 ALI panchromatic band with the Landsat 7 ETM+ band. The ALI panchromatic band is higher resolution, 10 meter versus 15 meter for ETM+, has 12-bit quantization as compared to 8-bit quantization for ETM+, and has a narrower spectral response than ETM+. The ETM+ panchromatic band covers both the visible and NIR wavelengths, whereas ALI includes only the visible wavelengths.

We plan to assess these differences in the sensors concentrating on an image from MAC, where we have particularly good ground data as well as a coincident IKONOS image. The existence of the IKONOS image gives us the option to include an extensive image resolution analysis using the 4 meter multispectral and 1 meter panchromatic IKONOS bands.

Evaluation of Hyperion water bands

Several indices have been proposed for measuring water content of vegetation from imagery. Examples are the Water Index (WI) (Penuelas, 1993, 1997) and the Normalized Difference Water Index (NWDI) (Gao, 1996). These indices involve the ratioing of narrow bands in the NIR and SWIR. The NWDI is a ratio of the 0.86 um and the 1.24 um bands while the WI is a ratio of the 800 um and 970 um bands. Bands from the Hyperion sensor will be used to test these ratios for a MAC scene where hyperspectral and thermal ground data are available. In addition, irrigation and weather information are available at MAC so water conditions of the crops under investigation can be estimated.

The Crop Water Stress Index (CWSI) (Jacskon, 1981) and the WDI are established water indices and the CWSI is currently used as a management tool for irrigation scheduling. Both these indices make use of the crop canopy temperature from infrared thermal measurements. We plan to compare these indices to the band ratioing water indices to see if there is a robust relationship between the two. Should there be, then the crop water stress could potentially be derived from satellite imagery without the need of a thermal band.

SUMMARY OF FINDINGS TO DATE

At present our current results include:

1) The difference in spectral response curves between equivalent ALI and ETM+ bands are minimal (highest RMSE 0.0066 for comparison of ALI band 4 to ETM+ band 4) and probably do not need to be taken into consideration when comparing equivalent ALI - ETM+ bands
2) Greater quantization of the ALI sensor reduces chances of band saturation in agricultural fields for targets of high reflectance.
3) Given the constraints of historical data analysis, data continuity across the Landsat 4 TM, Landsat 5 TM, Landsat 7 ETM+ and EO1-ALI is excellent. (see Table 9).
4) The new ALI SWIR band 5p may provide new information for agricultural crops.
5) ALI bands 4 and 4p are less affected by atmospheric water vapor than Landsat 7 ETM+ band 4.
6) The REL correction is a viable method for converting ALI data to ground reflectance when less accurate methods are not available.

PROJECT PUBLICATIONS

Bryant, R., M.S. Moran and S. McElroy (2001) Distinguishing shrub and grass vegetation using a combined panchromatic / multispectral approach. *Proc. Third International Conference on Geospatial Information in Agriculture and Forestery, November 5-7. Denver, Colorado.*

Bryant R. and M.S. Moran (2002) Data Continuity of Landsat-4 TM, Landsat-5 TM, Landsat-7 ETM, and Advanced Land Imager (ALI) sensors. *Proc. IEEE International Geoscience and Remote Sensing Synposium, 24th Canadian Symposium on Remote Sensing, June 24-28, Toronto, Ontario, Canada*

Bryant R., M.S. Moran, S. McElroy, C. Holifield, K. Thome, and T. Miura. (2002) Advanced Land Imager (ALI) and Landsat 7 ETM+ sensor band comparison and long term data continuity for three Landsat sensors and ALI. *I.E.E.E. Trans. Geosci. Rem. Sens. (submitted)*

Holifield C.D., S. McElroy, M.S. Moran, R. Bryant, and T. Miura (2002) Temporal and spatial changes in Grassland Transpiration Detected Using Landsat TM and ETM+ Imagery. *Canadian Journal of Remote Sensing (accepted)*

Holifield C.D., S. McElroy, M.S. Moran, R. Bryant, and T. Miura (2002) Temporal and spatial changes in grassland transpiration detected using Landsat imagery. *Proc. Intl. Soc. Rem. Sens. Env. Conference,8-12 April, Buenos Aires, Argentina.*

Moran, M.S., R. Bryant, C.D. Holifield, and S. McElroy (2002) Refined empirical line approach for retrieving surface reflectance from EO-1 ALI images. *I.E.E.E. Trans. Geosci. Rem. Sens. (submitted)*

Poster Presentations:

McElroy, S, S.M. Moran, R. Bryant and C.D. Holifield (2002) Agricultural Applications using IKONOS Imagery. *High Spatial Resolution Commercial Imagery Workshop March 25-27, Reston,* VA

Reports:

Bryant, R. and M.S. Moran (2002) Analysis of Hyperion sensor binned to equivalent ETM+ and ALI bands. Submitted to Jay Pearlman of TRW.

REFERENCES

Gao, B-C. (1996) NDWI – A normalized difference index for remote sensing of vegetation liquid water from space, *Remote Sensing of Environment,* 52:155-162.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter, P.J. (1981) Canopy temperature as a crop water stress indicator. *Water Resour. Res.* 17, 1133–1138.

Moran, M.S., R. Bryant, K. Thome, W. Ni, Y. Nouvellon, M.P. Gonzalez-Dugo, J. Qi and T.R. Clarke (2001) A refined empirical line approach for reflectance factor retrieval from Landsat-5 TM and Landsat-7 ETM+, *Rem. Sens. Env.* 78:71-82.

Moran, M. S., Clarke, T.R., Inoue, Y., Vidal, A. (1994) Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sens. Environ.*, 49(3): 246:263.

Penuelas, J., Filella, I., Biel, C., Serrano, L., and Save, R.(1993) The reflectance at the 950–970 region as an indicator of plant water status. *Int. J. Remote Sens.* 14:1887–1905.

Peñuelas, J., and I. Filella (1998) Technical focus:Visible and near-infrared reflectance techniques for diagnosing plant physiological status. *Trends In Plant Science*, 3(4):151–156.